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14. ABSTRACT

Current limitations in available data and computational tools have led to an on-going reliance on experimental measurements for injector design. Unfortunately, the mass flow rates typically encountered in rocket engines create sprays with high optical densities and render the vast majority of optical and laser techniques ineffective. Data has been obtainable through mechanical patternation, but the technique has limitations especially near the injector. Time-gated ballistic imaging has also shown promise in rocket injectors but produces only qualitative information about the mass flux. An x-ray radiographic technique with a high-power x-ray source (the Advanced Photon Source at Argonne National Laboratory) has been applied to these high-optical-density sprays. To achieve this testing a mobile flow facility was constructed; this facility simulates the rocket flows using water and nitrogen instead of fuel and oxidizer. The x-ray radiography technique can be applied in two ways. Time-averaged measurements provide information related to the mass flux and droplet velocity while time-resolved measurements have the ability to provide droplet size and velocity distributions. Both techniques have been applied to a specific injector type of interest in rocket propulsion, a gas-centered swirl-coaxial injector, and the results are used to show the complexities and strengths of x-ray radiography and illustrate the types of useful information that can be extracted, information that will aid in the development and improvement of rocket injectors.

15. SUBJECT TERMS

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The Use of X-Ray Radiography for Measuring Mass Distributions of Rocket Injectors

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Motivation

- **The near-injector region of many rocket injectors has not been quantitatively probed**
  - This region is where combustion occurs, so the conditions here set the combustion field and, therefore, engine performance
  - Currently, information is extrapolated from downstream interrogations
- **The lack of near-injector data is troubling since the extrapolated information is used to developing predictive tools to aid in engine design**
  - All of these tools have uncertainties and errors associated with them
  - These can be greatly compounded by the uncertainty and error introduced by extrapolation, but cannot be quantified due to the lack of data

Motivation

- **Most liquid rocket injectors operate at conditions (high flow rates and high pressures) which produce optically dense sprays**

  – Optically dense sprays scatter laser light so that insufficient light can be collected to make measurements

  – Probe based techniques are invasive and disrupt the flow creating large uncertainties and potentially altering important behavior

  – Remaining possible techniques (and some of the above) are qualitative

- **X-ray radiography allows quantitative results for equivalent path length (EPL) in the near-injector region and inside of the injector itself**

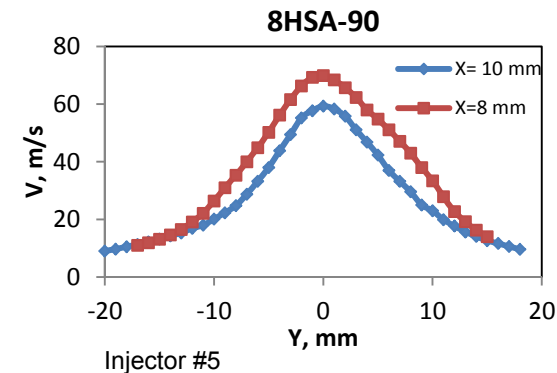 – The predominate interaction of x-rays with a spray is absorption, not scattering

Other Techniques

- **Ballistic Imaging can provide quantitative information on the size and shape of intact structures but ignores the droplet field**

Shadowgraphy

Ballistic Image
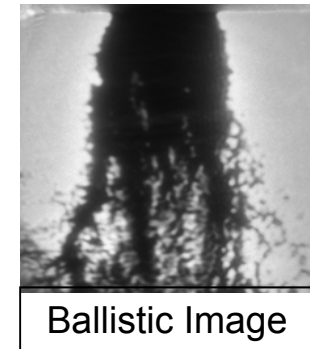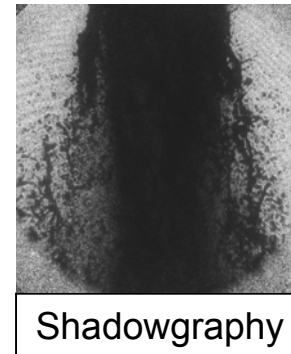
- **PDPA can be used in these sprays but typically not in the near injector region**

8HSA-90
Injector #5

- **Mechanical Pattenization is the only technique that can directly measure mass distribution but again not in the near injector region**
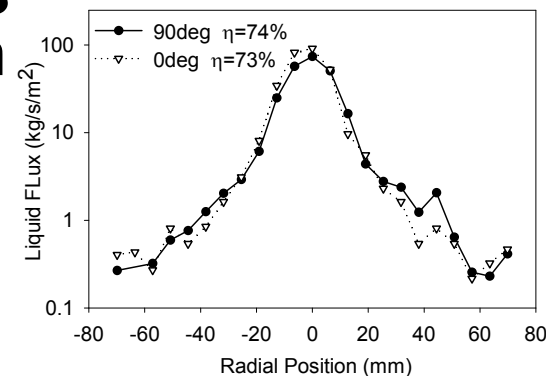
Previous X-ray Radiography Studies

- **To date most of the x-ray radiography studies have focused on diesel and gasoline injectors**

  - Leick, P., Kastengren, A.L., Liu, Z., Wang, J., & Powell, C.F., *11th Triennial International Conference on Liquid Atomization and Spray Systems,* Vail, Colorado, July 2009

  - Kastengren, A. L., Powell, C. F., Liu, Z., Moon, S., Gao, J., Zhang, X., and Wang, J., *22nd Annual Conference on Liquid Atomization and Spray Systems*, Cincinnati, Ohio, May 2010

- **Other studies include:**

  - **Aerated-liquid jets**

    - Lin, K.C., Carter, C., Smith, S., and Kastengren, A., *50th AIAA Aerospace Sciences Meeting*, Nashville, Tennessee, January 2012.

  - **Impinging jet injectors**

    - Halls, B. R., Heindel, T.J., Meyer, T.R., and Kastengren, A.L., *50th AIAA Aerospace Sciences Meeting*, Nashville, Tennessee, January 2012.

  - **Swirl-coaxial injector**

    - Eberhart, C. J., Lineberry, D. M., Frederick, R. A., and Kastengren, A. L., *48th AIAA Joint Propulsion Conference*, Atlanta, Georgia, August 2012.

- **First time used in a spray with a strong gas phase**

Mobile Flow Laboratory

- **Self contained mobile system capable of delivering up to one kg/s of H_2O & GN_2 at pressures in excess of 200 atmospheres**
  - Requires only power, LN_2, and exhaust from host facility.
  - System fully rated to 408 atm (Allows more GN_2 storage)
  - Dedicated Allen-Bradley control & Pacific Instruments data acquisition systems
  - Remote operation
  - High speed abort system on all data channels for added pressure safety
  - System is on wheels and can be assembled in under 2 days
 - Ran almost continuously (24 hours/day) for two weeks

X-Ray Radiography Details

- **Experiments performed at the 7-BM beamline of the Advanced Photon Source**

- **Synchrotron bending magnet to produce polychromatic (white beam) which is made into a monochromatic beam**
  - Monochromator is tunable between 5.1 keV to 12 keV
  - 10 keV used for the present study based on the absorption of the anticipated test conditions
  - Beam is small and has a FWHM of 5 x 6 microns
  - X-ray flux of 2.5×10^{11} photons/s/mm^2

- **Both time-averaged and time-resolved measurements can be made**
  - The system was not optimized for time-resolved measurements as only time-averaged ones were originally planned.

- **Beer's law is used to convert these measurements into an equivalent path length of water (EPL)**
  - Path length is the average across each measurement, 4 seconds for time averaged results and 1 microsecond for time-resolved.

Test Setup & Matrix

- **Normalization by the the intensity of incident light performed in two steps**

  - Titanium foil: beam intensity variations during a scan

  - Zero absorption case: average signal level from the 5 points in the scan with the highest transmission (Outside the spray-accounts for gas absorption)

Near Injector Optics Layout
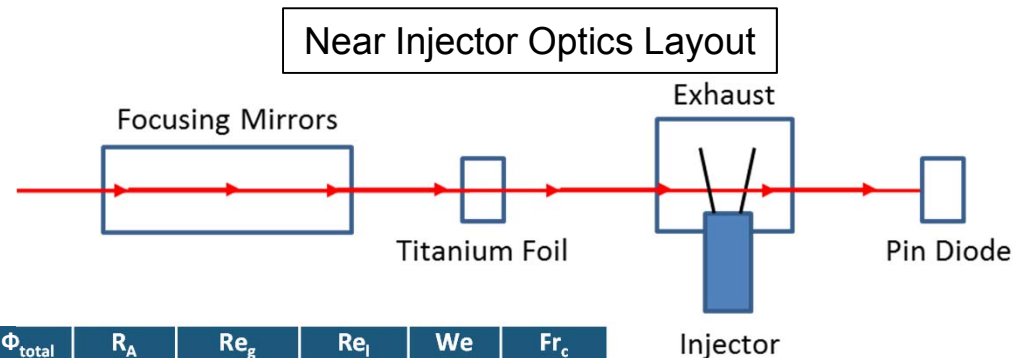
| Condition	$\dot{m}_g$ (g/s)	$\dot{m}_l$ (g/s)	Φ_{total}	R_A	Re_g	Re_l	We	Fr_c
4H-60	46	37	58	0.299	380,000	2,100	42	0.158
4H-90	46	30	86	0.299	380,000	1,800	29	0.158
4H-120	46	26	117	0.299	380,000	1,500	21	0.158
4H-145	46	23	141	0.299	380,000	1,400	17	0.158
8HSA-60	46	32	58	0.261	380,000	2,200	42	0.162
8HSA-90	46	26	89	0.261	380,000	1,800	28	0.162
8HSA-110	54	26	107	0.261	440,000	1,800	28	0.162
8HSA-120	46	22	120	0.261	380,000	1,600	20	0.162
8HDA-60	46	49	60	0.406	380,000	2,100	41	0.145
8HDA-90	46	40	91	0.406	380,000	1,700	27	0.145
8HDA-120	46	35	118	0.406	370,000	1,600	21	0.145
8HDA-130	33	26	128	0.406	260,000	1,100	12	0.145
8HDA-145	46	31	148	0.406	380,000	1,364	17	0.145
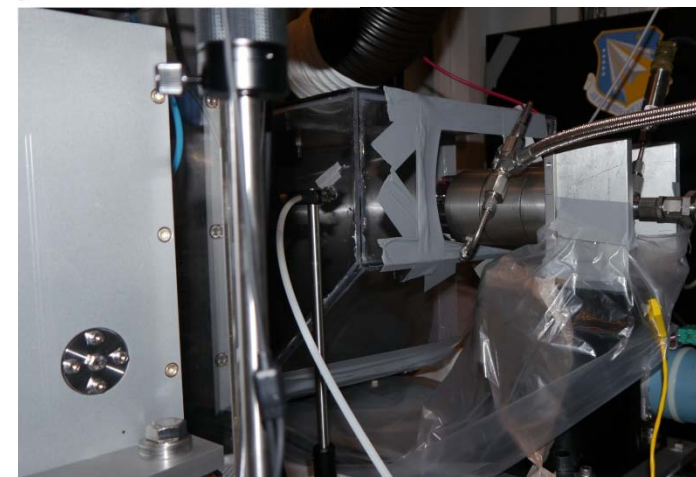
Equivalent Pathlength

- **Two types of measurements were made—time-averaged and time-resolved**
  - Difference is the length of time over which the signal is integrated, either 1 μs or 4 s

- **Resulting measurements are reported in Equivalent Path Length (EPL) which is the pathlength-integral of the amount of water in the beam**

- **EPL is a function of velocity, droplet size and mass flux distribution**
  - A single-droplet example illustrates how these effects can be convoluted
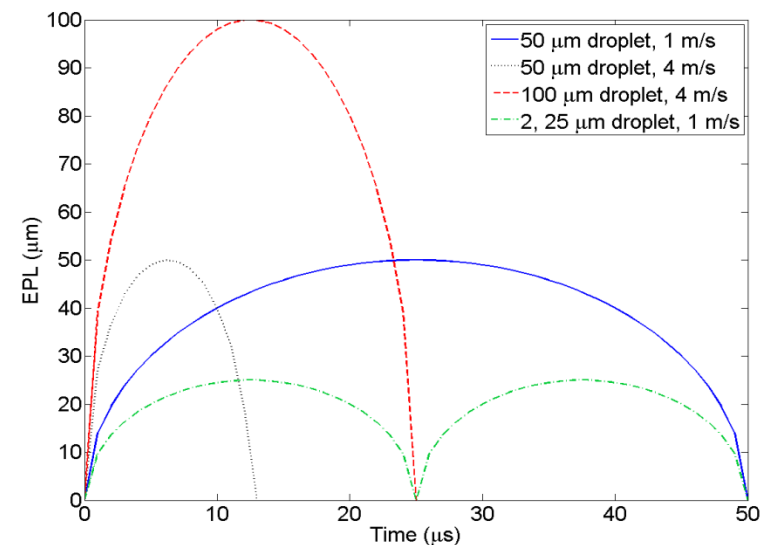
Equivalent Pathlength

- **When a full spray exists, interpretation is even more complex**

- **Simulations of EPL were run to understand the effect of the velocity and mass distribution on the EPL profile**

  – Simulation assumes axisymmetric mass & velocity profiles & divides the spray into a grid

  – Droplet size is assumed uniform across the spray

  – Vertical spacing between droplets in each cell is set to achieve correct mass flux and velocity
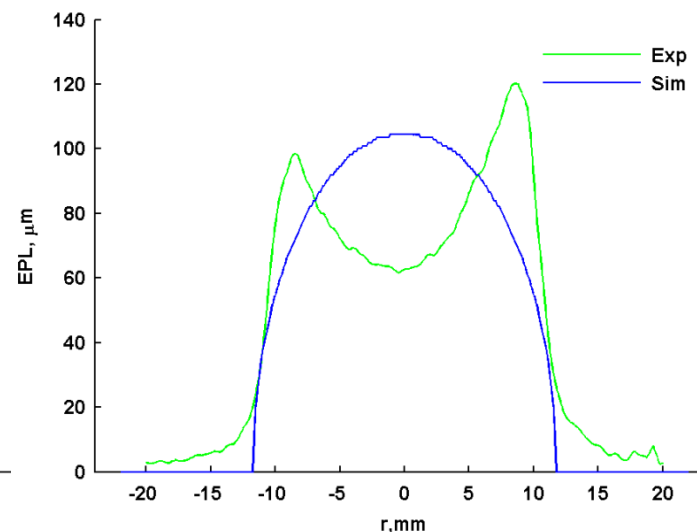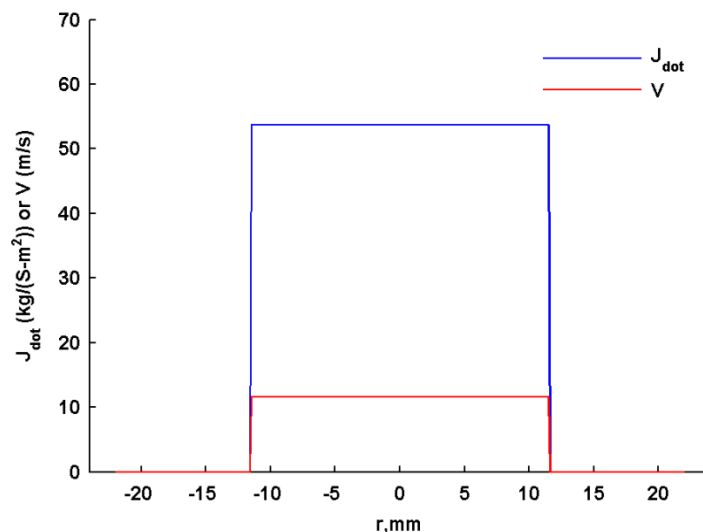
8HSA-120
(5mm Downstream)
D_d=75 µm
$\dot{m}_L$=35 g/s
V_{ma}=11.6m/s

EPL Simulation
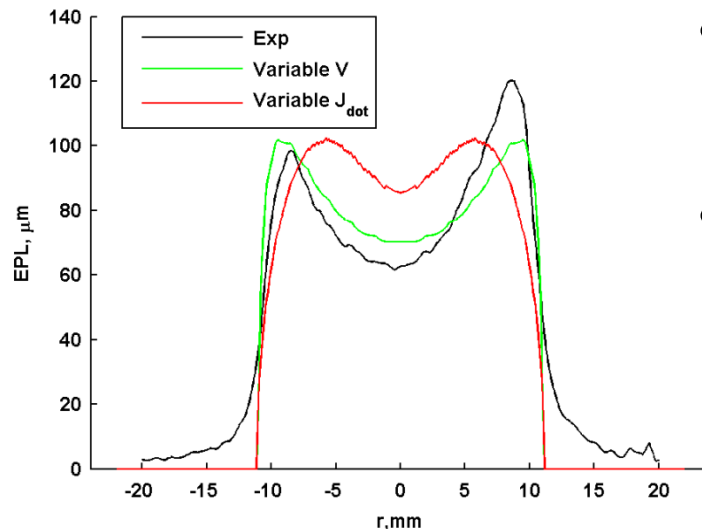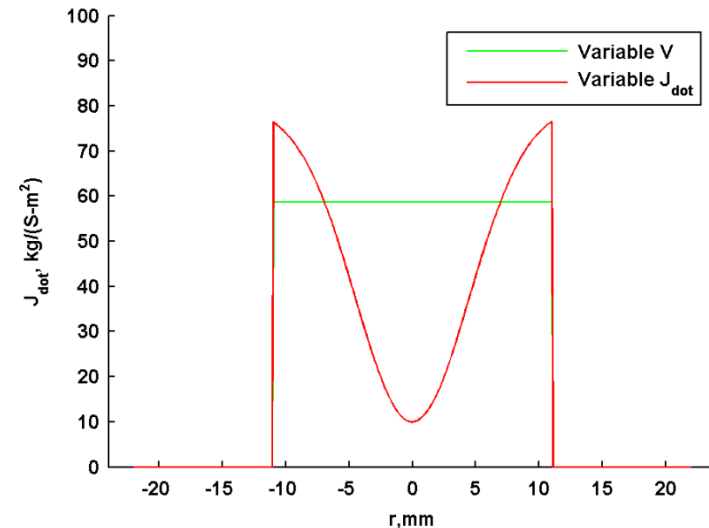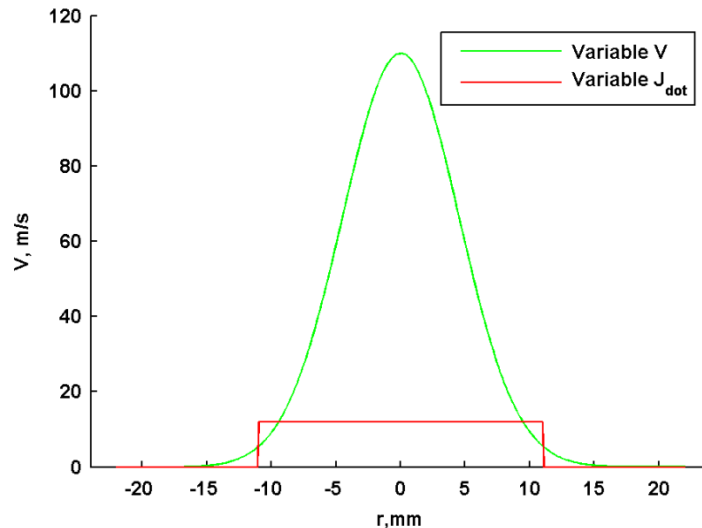
- **The center valley in EPL can not be explained by a mass deficit alone**

- **The EPL deficient in the spray center is largely caused by high center line gas post velocity**
  - 300 m/s gas velocity at gas post exit
 - Droplet diameter (D_d) assumed 50 μm for both Cases

Geometry of Demonstration

- **To demonstrate the technique and what it can provide, we've chosen a specific gas-assisted atomizer, a Gas-Centered Swirl-Coaxial Injector**
  - Tangential liquid inlets create a swirling, annular fluid which is atomized by high-velocity unswirled gas
- **Momentum flux ratio (the main scaling parameter) was varied between 60 and 145 with 4 different geometries**
  - Geometries represent changing the number of inlets, the inlet size and the inlet area (swirl number)
  - Outlet size also examined, but not presented today

outlet wall
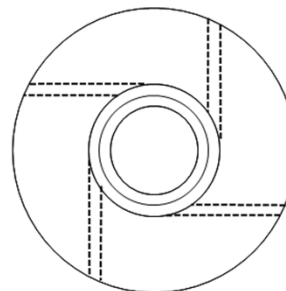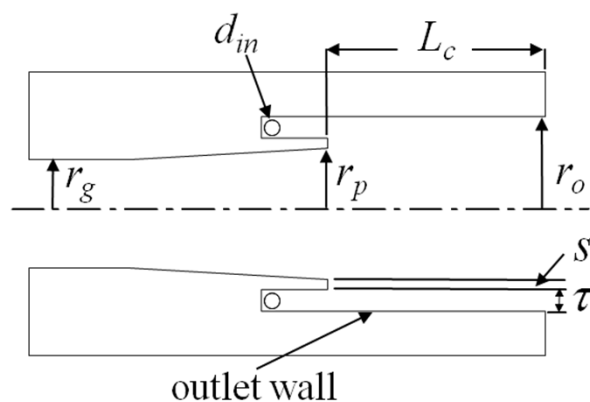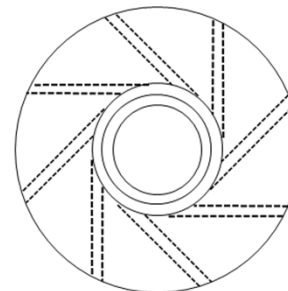
4 tangential inlets   8 tangential inlets

$r_g = r_p = 6.35$ mm
$L_c = 33.0$ mm
$r_o = 9.53$ mm
$S = 1.52$ mm
$\tau = 1.65$ mm
$d_{in} = 1.6$mm, 4H
$\quad = 1.6$mm, 8HDA
$\quad = 0.989$mm, 8HSA

Gas-Centered Swirl Coaxial Injectors

- **Why Gas-Centered Swirl-Coaxial (GCSC) injectors?**
  - Interest exists around the world in designing new LOX-Hydrocarbon rocket engines using an OX-rich staged-combustion cycle
    - Recent papers from Russia, China, S Korea and multiple US groups
  - Successfully used in Russian rocket engines employing a staged-combustion cycle (e.g., RD-170)
  - Such a design and typical mixture ratios result in a high speed gas flow which is available to atomize the liquid hydrocarbon fuel

- **BUT, design criteria and scaling laws are still needed over a range of conditions and geometries**
- **Previous work by the authors using cold flow techniques have investigated the effect of numerous geometric variations on the size, shape, and frequency of the wall bounded film and spray**
  - Cold flow techniques include laser sheet imaging of the film, shadowgraphy of the spray, limited PDPA
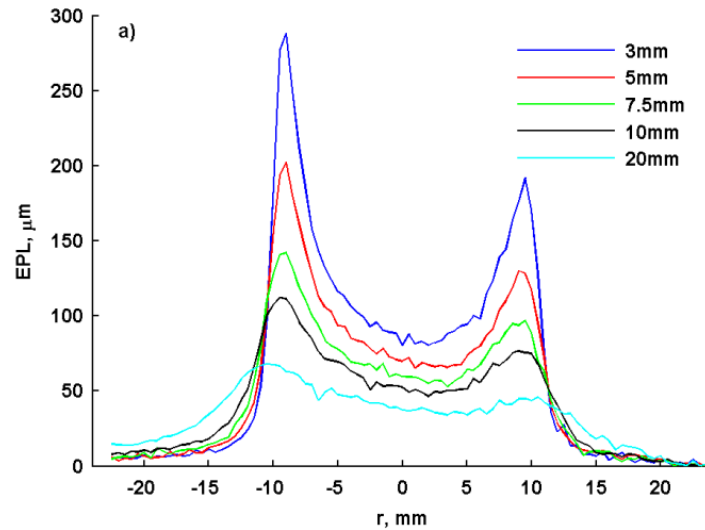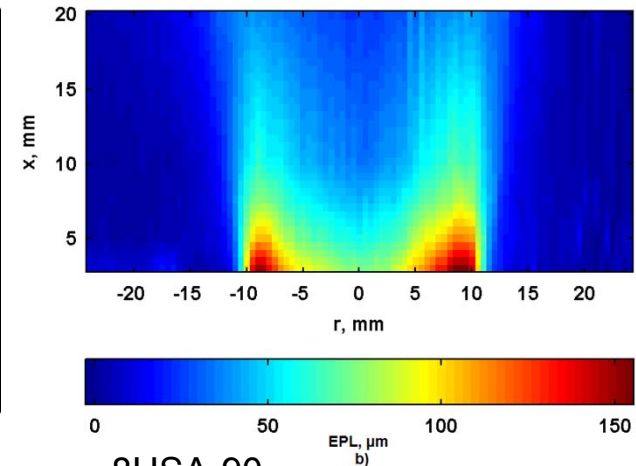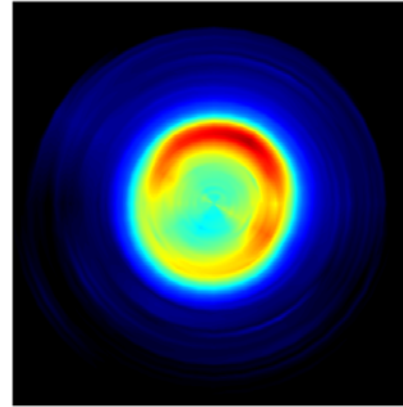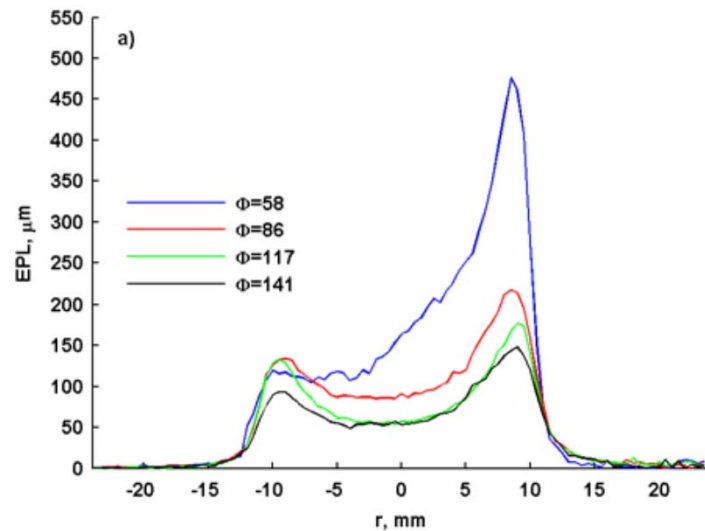
8HSA-90

8HSA-90

8HSA-120

8HSA <?>

- **All sprays tested are not uniform in velocity and/or mass (as expected)**
- **Downstream evolution rigorously captures spray edge & quantifies angle**
- **Momentum flux ratio increases improve atomization and uniformity**
- **Quantifies departures from uniformity**

Mass Weighted Velocity

- **Droplets across the entire spray are undergoing acceleration in the near injector region**
  - Acceleration can be quantified by the mass-weighted velocity (V_{ma})
  - V_{ma} obtained by dividing $\dot{m}_L$ with the integral of the average projected liquid density profile
  - Between initial gas-liquid contact and 3 mm downstream acceleration is on the order of 1,000 m/s^2
 - Between 3 mm and 10 mm acceleration is on the order of 10,000 m/s^2
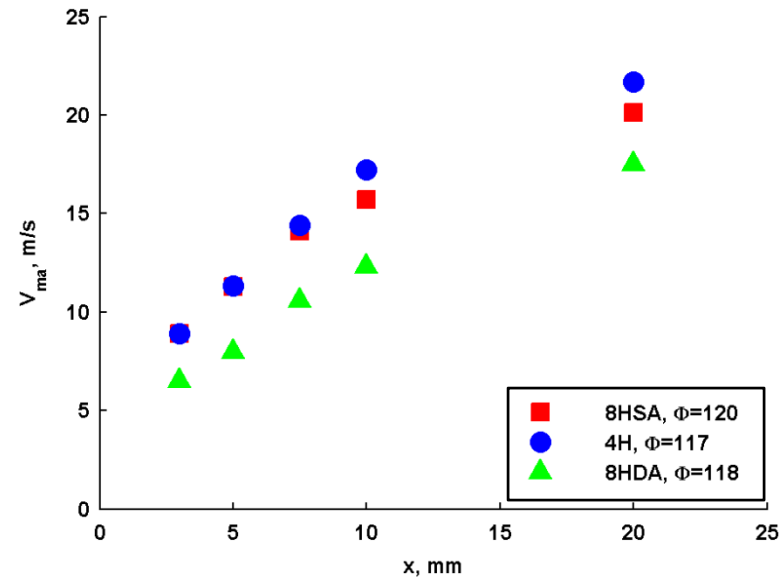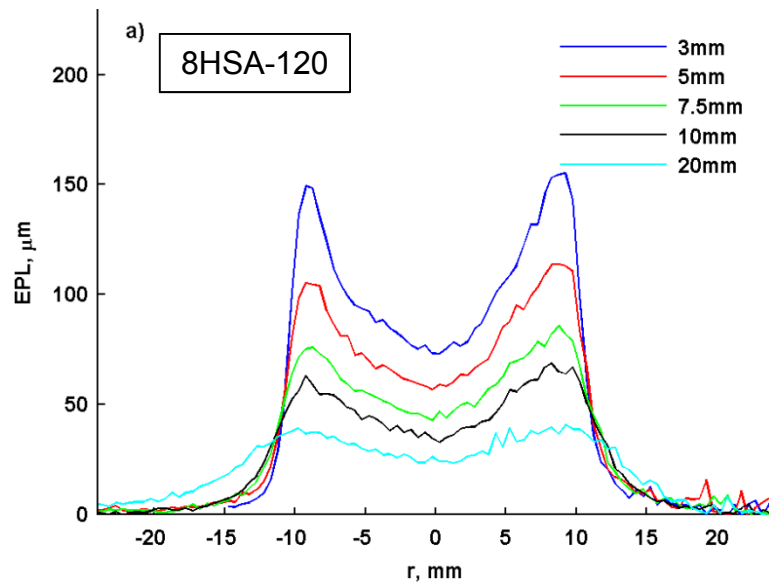
Time Resolved: A Single Droplet

- **Can the x-ray radiography provide spray statistics?**
  - Prior radiography results have not extracted droplet information

- **Consider the simplest case of a single droplet moving thru the beam**
  - The peak of the path length corresponds to the droplet diameter
  - The elapsed time of departure from 0 path length relates to the velocity

- **A simple approach is taken to get droplet size and velocity from the data even where multiple droplets are in the beam**
  - Each peak in the data is a droplet
  - Its diameter is the offset from the bounding valleys (minimum)
  - Its velocity is related to the time between bounding valleys
 - This produces known biases, but demonstrates power of measurement
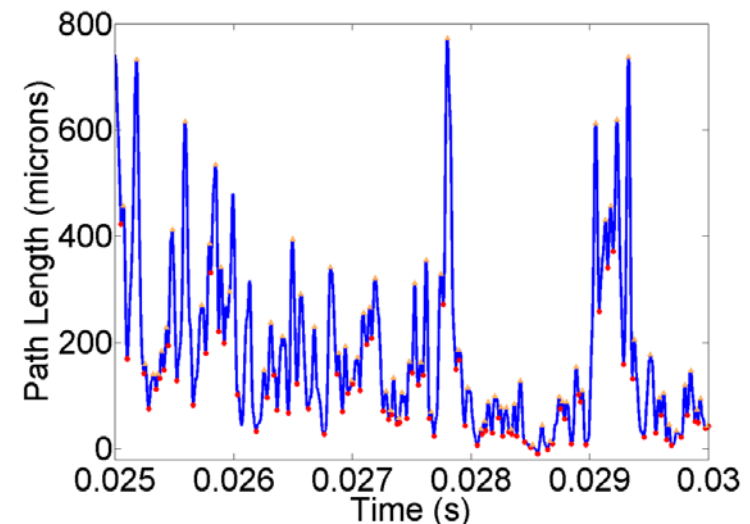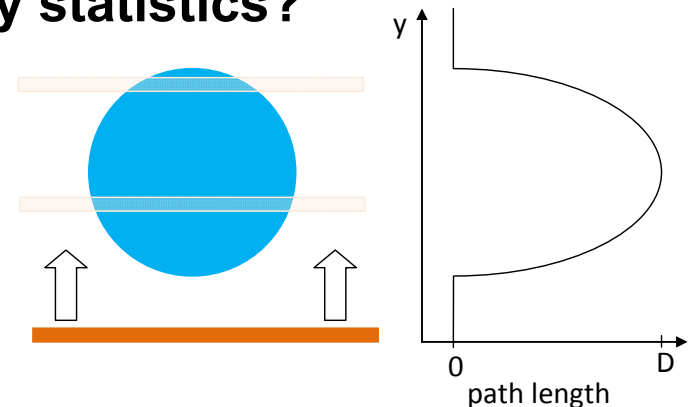
Mean Droplet Diameter

- **Current time-resolved processing has some limitations due to its simplicity**
  - Limitations in the velocity of a droplet that can be resolved as a individual unit
  - This limit is strongly tied to droplet diameter—so the smaller the droplet the lower the velocity that can be resolved

- **Time-averaged EPL and calculated mean diameter is not the same**
  - Mean of the curve is different from time-resolved curve's peak
  - However, general behavior should be similar in many situations including the present one and should provide some confidence in the technique
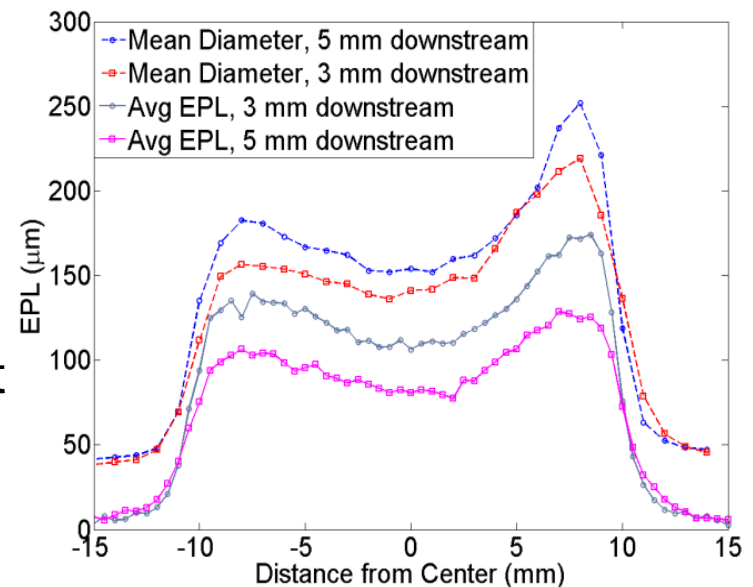
Improving Injector Understanding

- **Simplified method means that the current assessments are only semi-quantitative, but useful results exist**

  - Changing the liquid inlet size has little or no effect on the atomization and droplet-size distribution

  - However, changing the liquid inlet area (swirl) has a large effect on droplet-size distribution

  - Nonuniformities show increase in droplet size as well as number during pulses

Low Swirl   High Swirl

Backwards titles
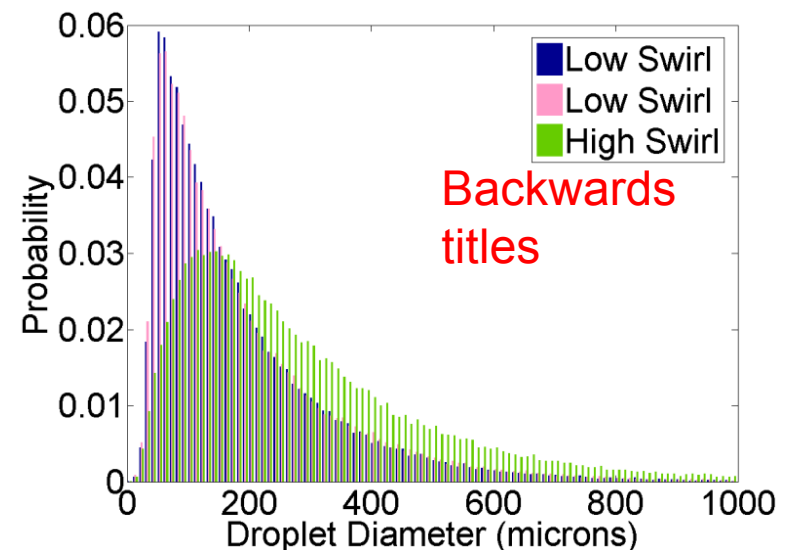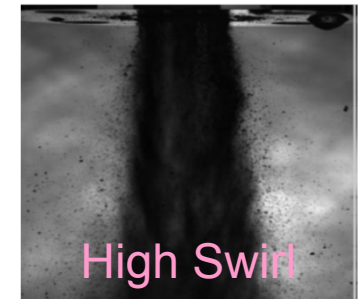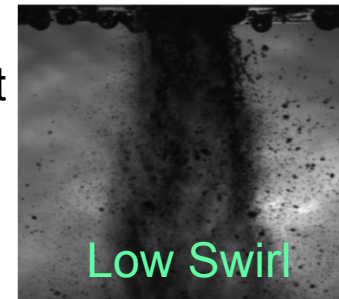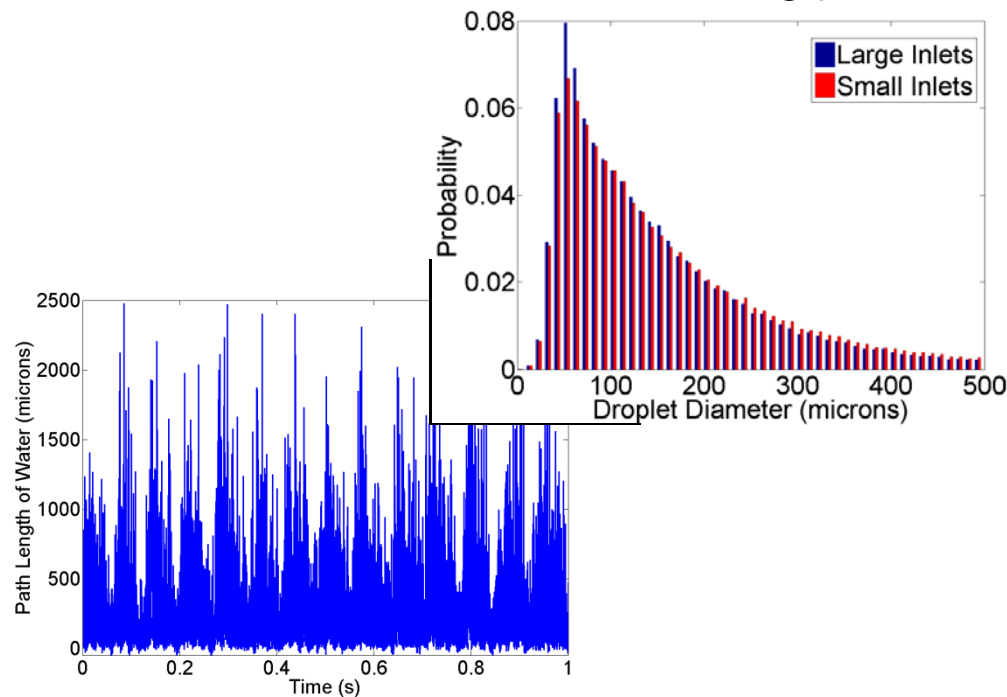
X-Ray Conclusions

- **X-ray radiography can be used to quantitatively examine the near injector region of high-optical-density injectors**

- **EPL deficits in the spray center were shown to be caused by high velocities in the middle of the spray**

- **Time-averaged measurements enable quantification of many important overall spray aspects**

  - Spray boundary (width) and spray angle

  - Improvement of atomization and uniformity with momentum flux ratio increase

  - Departures from uniformity

  - Mass-averaged velocities and acceleration

  - However, the mass and velocity remain coupled, so careful interpretation is required

X-Ray Conclusions

- **Time-resolved radiography might be able to help decouple mass & velocity by providing droplet size and velocity distributions**

  - A simple approach demonstrates the utility of the technique

  - Able to capture changes in mean droplet diameter and droplet size distributions

  - Additional insight into pulsing nonuniformities was provided

- **X-ray radiography is enabling insight not achievable with other available diagnostics**

Acknowledgements

- **A portion of this research was performed at the 7-BM beamline of the Advanced Photon Source, Argonne National Laboratory. Use of the Advanced Photon Source at Argonne National Laboratory was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.**

- **Special thanks for their assistance in setting up and data collection during the testing campaign at Argonne National Laboratory**

  – Benjamin Halls (Iowa State University)

  – Chad Eberhart (The University of Alabama in Huntsville)

  – William Miller (Kettering University)


7-BM

Back-Ups

Nondimensional Parameters

- The relevant nondimensional parameters can be obtained by nondimensionalizing the force balance for a surface disturbance by the liquid inertia $(\rho_l v_l^2 \tau^2)$ and multiplying by τ^2/A_{dist} to eliminate disturbance parameters from the aerodynamic force term

- Assuming worst case scenario for disturbance size and that all constants are of order 1:

Lift

Drag

Surface Tension

Surface Tension

Friction
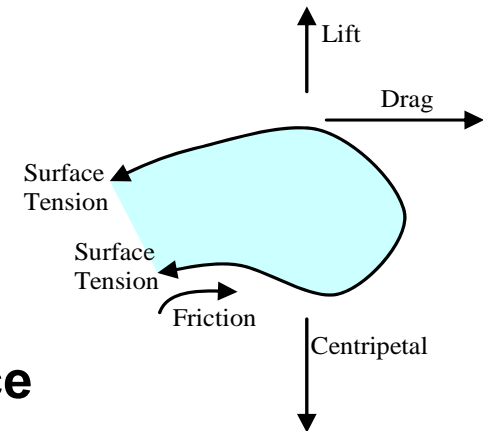
Centripetal

| Aerodynamic | | Viscous | | Centripetal | | Surface Tension |

$$\Phi = \frac{\rho_g v_g^2}{\rho_l v_l^2} \qquad \frac{1}{\text{Re}_l}\frac{v_g}{v_l} \qquad Fr_c = \left(\frac{v_{Tan}}{v_{Total}}\right)^2\left(\frac{\tau}{r_o}\right) \qquad \frac{1}{We}$$
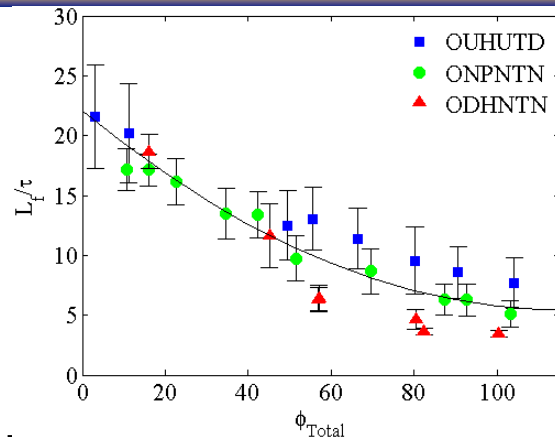
Example with the 8H-ONPNTN Geometry:

Force	Aerodynamic Φ_{total}	Liquid Phase Viscous	Centripetal Fr_c	Surface Tension
Value	114	0.1	0.2	0.02

- **GCSC injectors operate in a regime where aerodynamic forces are dominant**

Momentum Flux Ratio

$$\Phi_{Total} = \frac{\rho_g v_g^2}{\rho_l v_l^2}$$

Name	r_o (mm)	τ (mm)	r_p (mm)	s (mm)
ODHNTN	7.62	1.65	4.45	1.52
ONPNTN	9.53	1.65	6.35	1.52
OUHUTD	11.4	1.32	7.24	2.87

- Swirl alters the shear between the liquid and gas phase which must be taken into account in Φ

- Difficult to define due to complex compressible flow field

- Use of single velocity to describe flow field questionable

- Best collapse of film lengths found using total liquid velocity and a calculated gas phase velocity and static density

- Total liquid velocity calculated using measured mass flow rate and assuming conservation of momentum between the tangential liquid injector holes and liquid cup exit

- Using the measured mass flow rate, total temperature and static pressure in the gas plenum static density was calculated assuming 1D flow and a calorically perfect gas

180º Radial Profiles

- **Due to space constraints at beamline, testing was conducted with the spray flowing horizontal**
- **Two scans with 180º rotation to investigate potential gravity effects**
  - 180º flipped about *r=0* for comparison
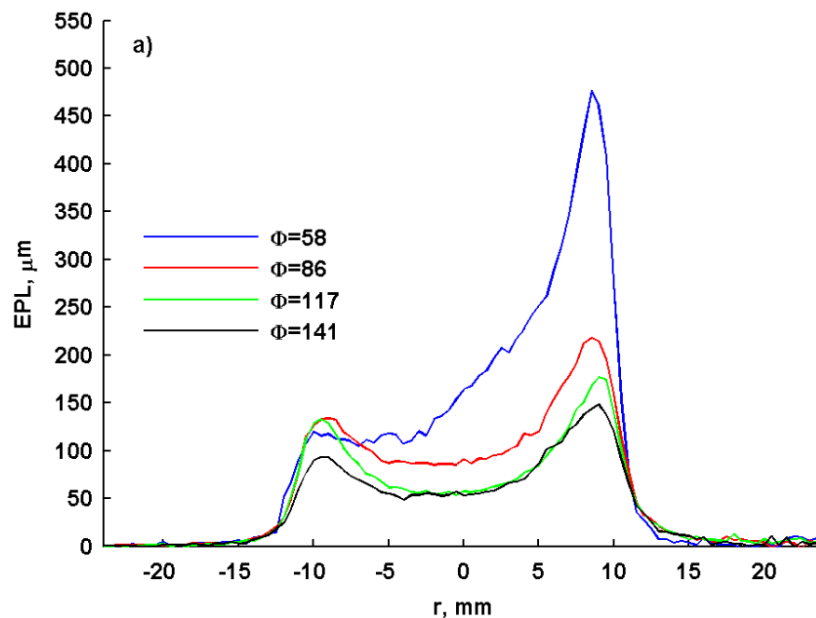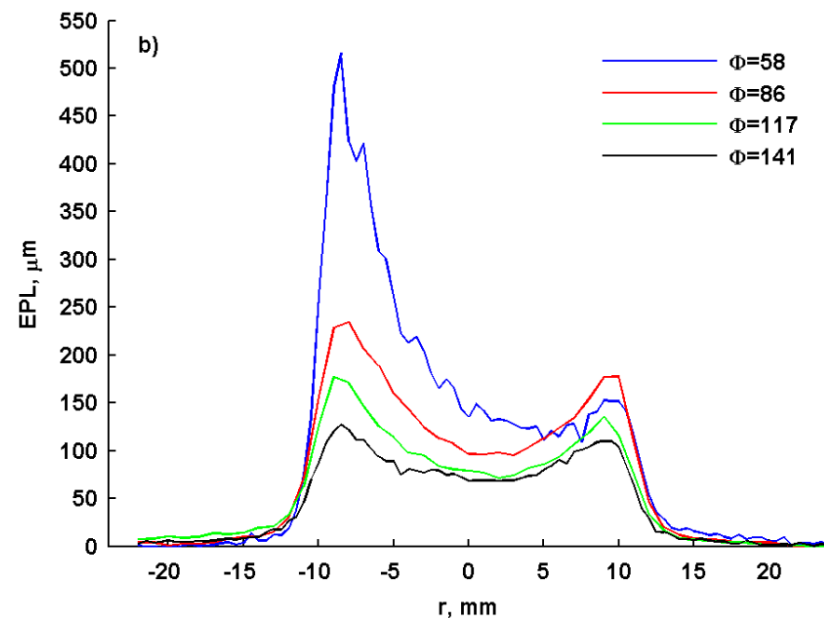

5mm downstream

8HSA-90

8HSA-120
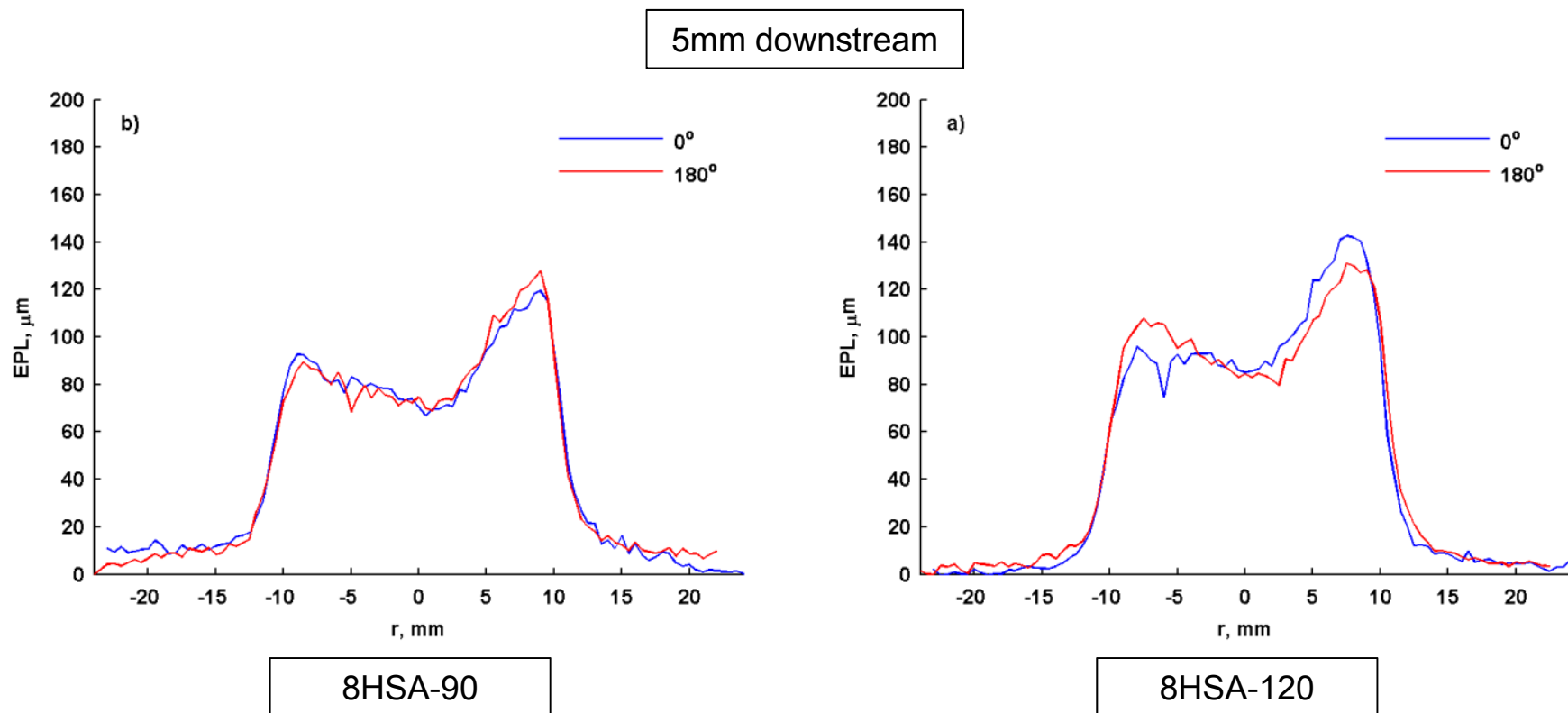
Momentum Flux

- **Uniformity improves with increasing momentum flux ratio (Φ) up to a point**
  - Decrease in EPL profile as Φ increases is due to the decrease in the liquid mass flow rate
  - Expected from earlier work / views downstream
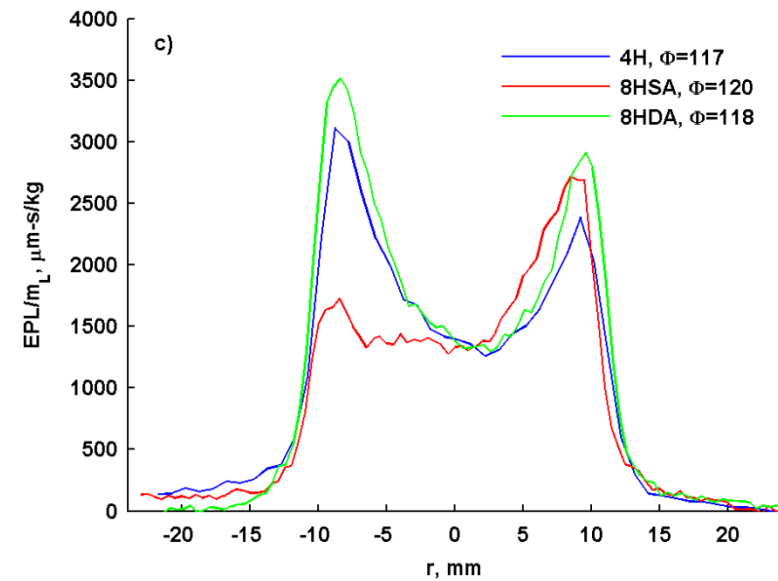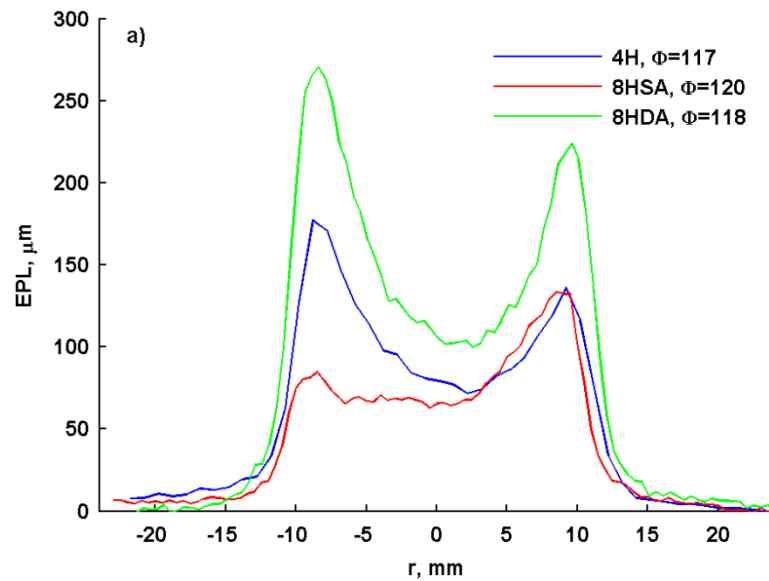
4H-ONPNTN, 5mm downstream

60° orientation

0° orientation

Swirl

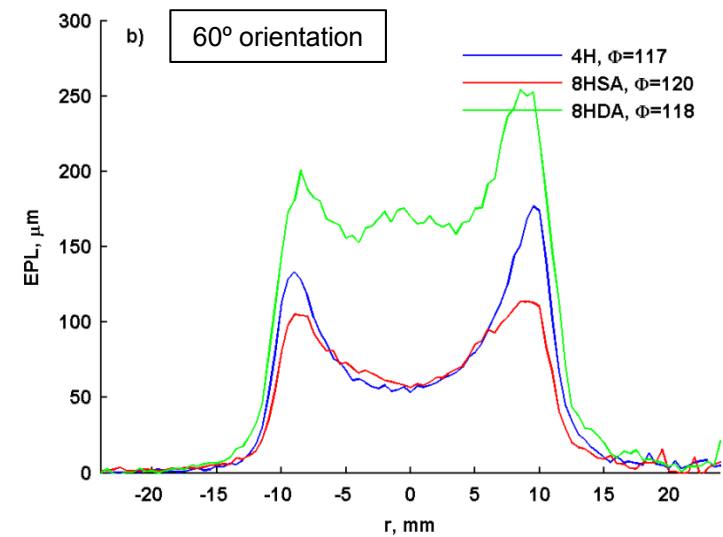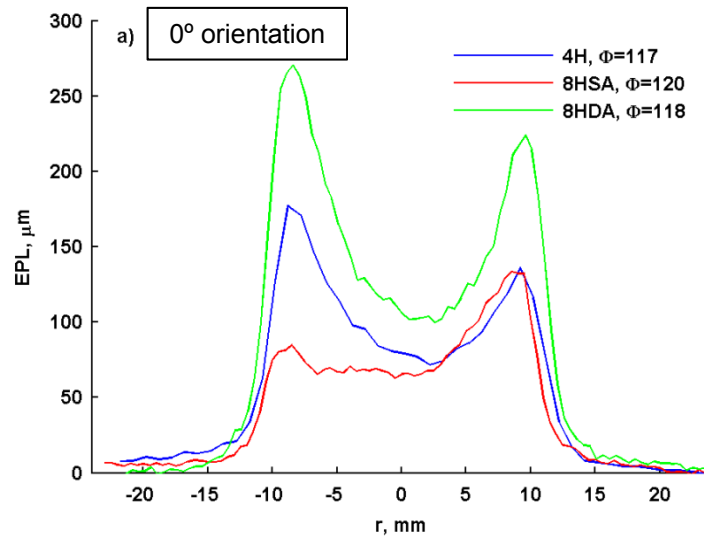0° orientation, 5 mm downstream

R_A=0.299, 4H-120 R_A=0.261, 8HSA-120 R_A=0.406, 8HDA-120
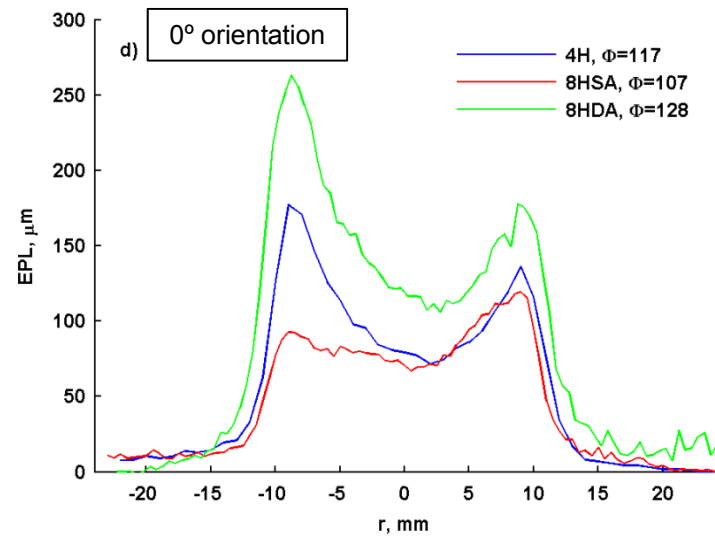
Spray Symmetry & $\dot{m}_L$

a) 0° orientation
- 4H, Φ=117
- 8HSA, Φ=120
- 8HDA, Φ=118

b) 60° orientation
- 4H, Φ=117
- 8HSA, Φ=120
- 8HDA, Φ=118

d) 0° orientation
- 4H, Φ=117
- 8HSA, Φ=107
- 8HDA, Φ=128

5mm downstream

$\dot{m}_L$=26 g/s
4H, V_{gp}= 295 m/s
8HSA, V_{gp}= 309 m/s
8HDA, V_{gp}= 250 m/s

Comparison to Time-Averaged

- **Time-averaged results can be related to droplet diameters extracted from time-resolved data**
  - Correlation is not exact because periods of no droplets are included in the time-averaging
  - For a single droplet, the mean path length would be $\pi D/4$

- **Mean diameter is LARGER which indicates it is being overestimated by the simple procedure**
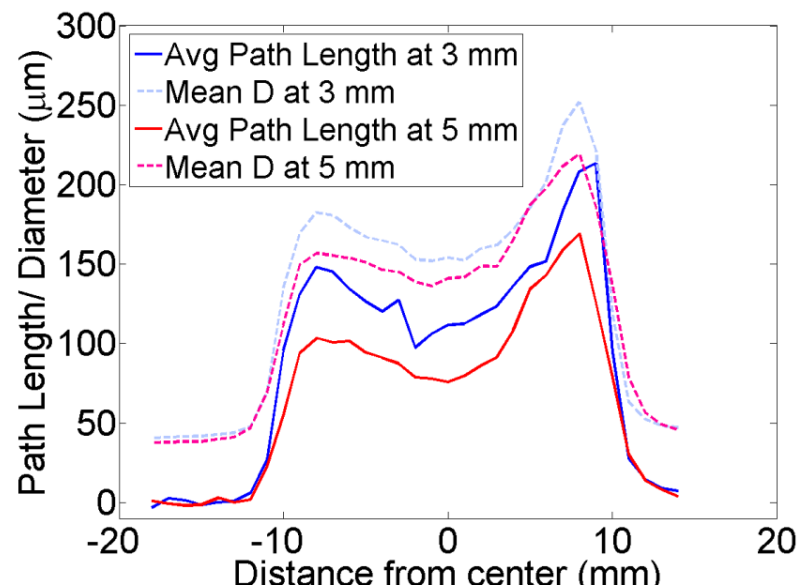

– Could be a result of upward diameter bias

– Most likely the result of not measuring very small droplets (noise and resolution)

– Both will be improved upon with the new DAQ at APS and new data processing here at AFRL

Velocity as a Function of Diameter

- **There is a strong correlation between droplet diameter and velocity in these results**

- **At least some of this is artificial and a result of the current experimental set-up**

  - Velocity as a function of diameter does not change with axial (downstream) distance

  - Larger droplets are faster and have a wider range of velocities, which is not what would be expected for a shear-driven spray

  - Happens because droplets must be in beam 10 microseconds to be measured as an independent droplet in the current simple assessment
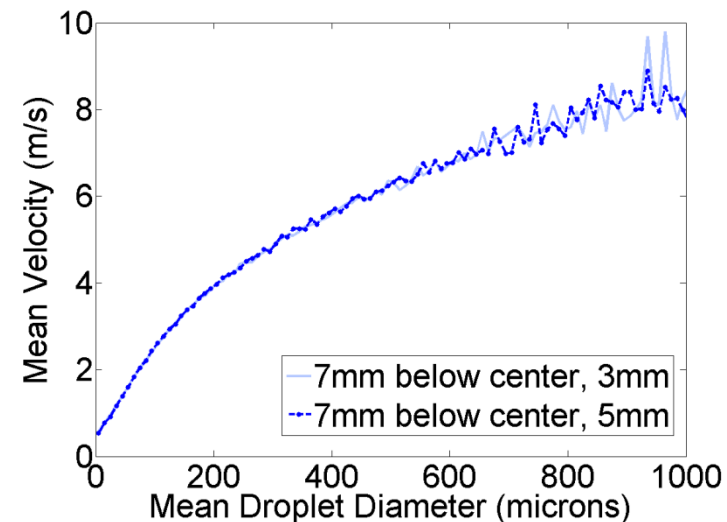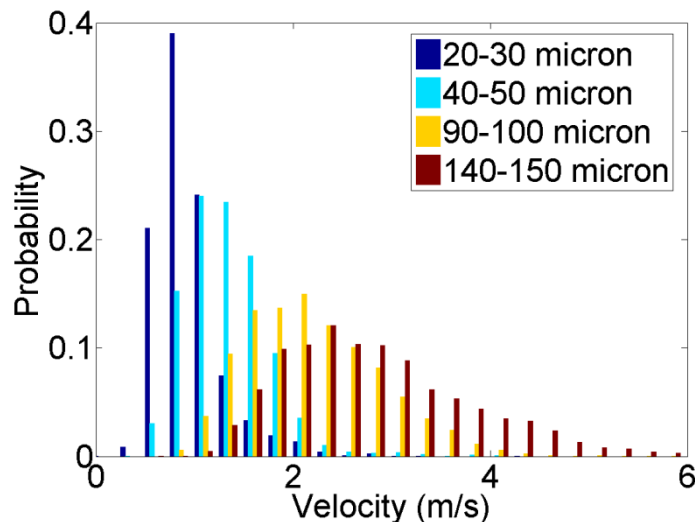
Simple Procedure

- **Automated Matlab process was developed to find peaks and troughs and translates them to droplet diameter and velocity**

- **Other assumptions include**
  - Droplets are spherical and travel so that their centers are captured by the beam
  - Droplets have only axial velocities

- **Signal-to-noise ratio not optimized here, so a running-average is taken to smooth data**
  - Lower x-ray energy will be used in the future to improve the signal-to-noise and hopefully remove the need for filtering
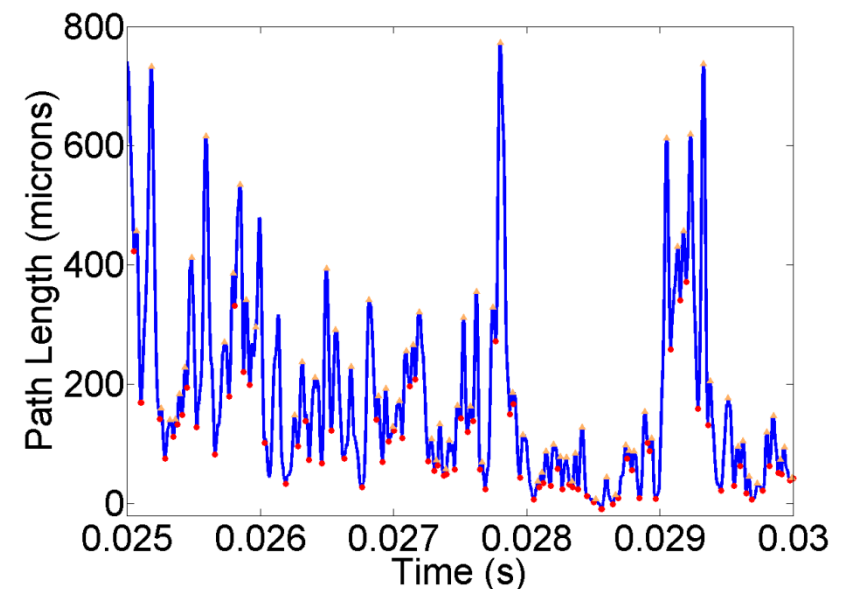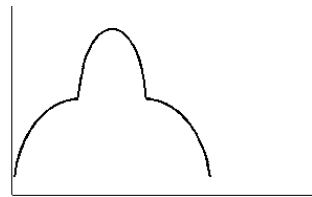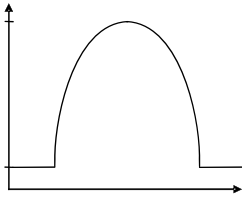
Biases

- **Obviously, there are multiple droplets in the beam at one time (troughs are not 0), so simple procedure introduces biases**

  - If 2 droplets are same velocity and size and enter simultaneously, the procedure finds 1 droplet of double size and velocity

  - If 2 droplets are the same but entry is offset then an "extra" droplet is found and there is a bias to underestimate diameter

  - If 2 droplets are same size and entry time but different speeds then the faster droplet appears too large and fast and the slower droplet has an overestimated velocity

- **Improvements could be made using a curve-fitting procedure similar to in spectroscopy**

  - However, this is complex and time consuming (therefore, it is currently incomplete)

Noise Level

- **The automated procedure finds "droplets" in the case where no water is flowing**

  - Mean diameter is 23 microns and 95th percentile diameter is 35 microns

- **Droplets are also found outside of the main spray**

  - Spray edge is difficult to determine precisely

  - These values are larger than with no water, 95th percentile is 44-60 microns depending on the test

  - Mist does recirculate in the exhaust area; this can be mollified by improved exhaust